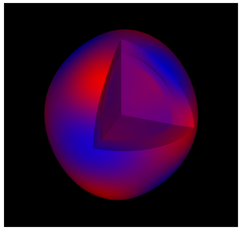
Stars and their variability, observed from space

Vienna, 19-23 August 2019



Asteroseismology of hot subdwarf and white dwarf stars

The successes of forward modeling approach with parametrized static models

Valerie Van Grootel[1]

S. Charpinet[2], G. Fontaine[3], P. Brassard[3], N. Giammichele[2], E.M. Green[4], M. Latour[5] & S.K. Randall[6]

(1) STAR Institute, Université de Liège, Belgium
(2) IRAP, Toulouse, France
(3) Université de Montréal, Canada
(4) University of Arizona, USA
(5) Universität Göttingen, Germany
(6) European Southern Observatory, Germany

Outline

I. Pulsations in hot subdwarf and white dwarf stars
   a. Introduction
   b. Some marking results from space observations

II. Models and method for asteroseismic modeling

III. Testing the seismic results with GAIA

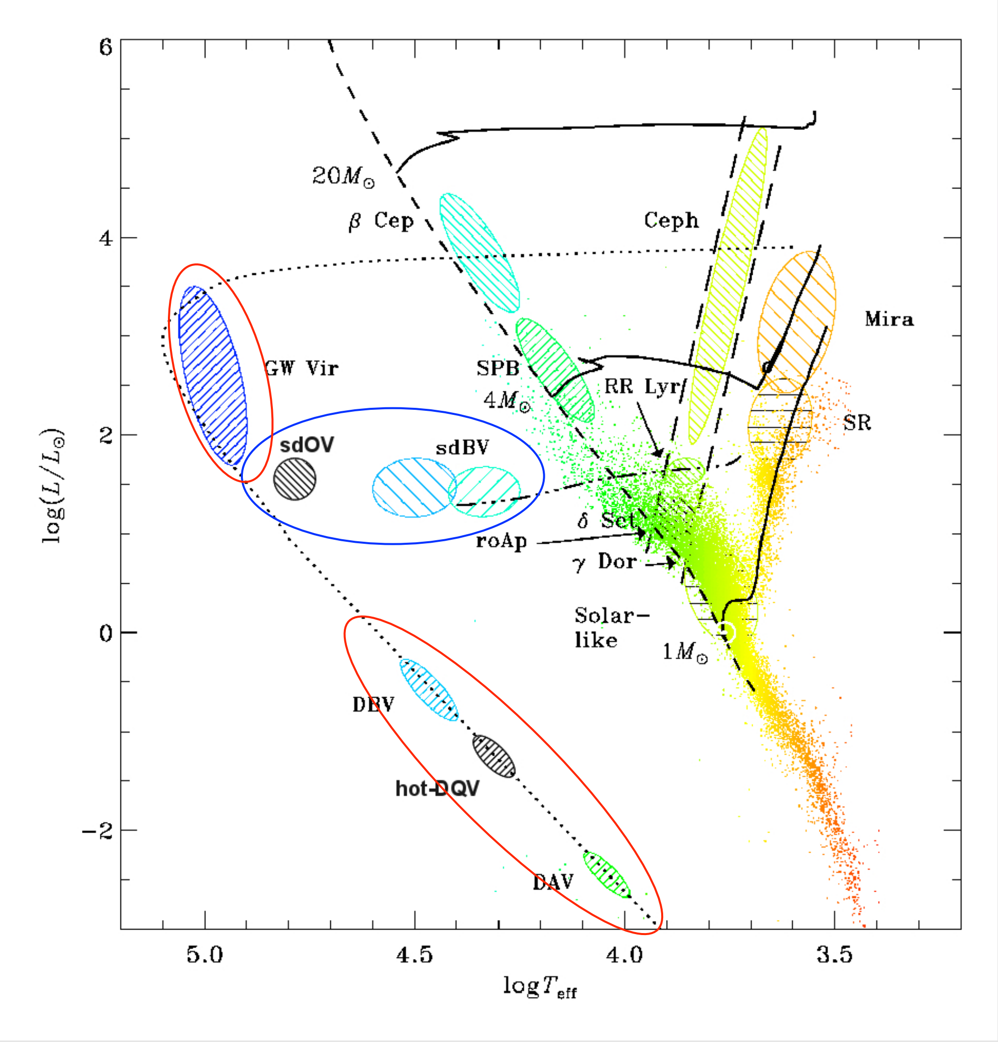
IV. Seismic modeling of white dwarfs

V. Conclusions & prospects

Pulsations in hot subwarfs and white dwarfs

Hot subdwarfs (sdB & sdO): He-burning objects with T_{eff} > 20,000 K and log g ~ 5 – 6

White dwarfs: cooling objects, fate of ~98% of the stars in Universe



Various classes of pulsators

sdB stars (V~15):

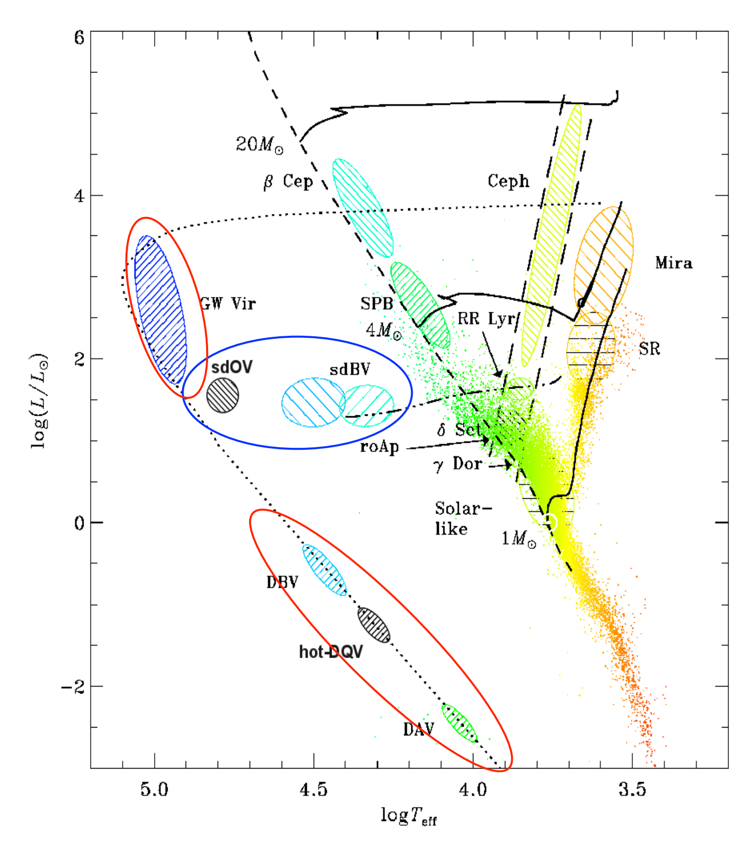
> short-periods (P ~ 80 - 600 s), A ≤ 1%, p-modes (envelope), discovered in 1997
> long-periods (P ~ 30 min - 3 h), A ≤ 0.1%, g-modes (core), 2003. **Space observations required !**
+ hybrid pulsators

sdO stars (V~15):

> 5 in ω Cen (2011), 3 in the Galactic field (2006)
> short-periods (80-140s), p-modes, no successful seismic modeling so far

White dwarfs (V~18):

> GW Vir (He/C/O atmospheres), 1979, T_{eff} ~125,000 K
> DBV (He atmo), 1982, T_{eff} ~25,000 K
> Hot-DQV (C-rich/He atmo), 2007, T_{eff} ~20,000 K
> DAV (H atmo) or ZZ Ceti, 1968, T_{eff} ~12,000 K



All g-mode pulsators
(few hundreds to few thousands seconds periods)

Pulsations in compact stars: the space input

sdB stars:

> **Kepler**: discovery of **18** sdB pulsators, K2: discovery/observations of **36** sdB pulsators, g-modes and hybrids + **1** g-mode pulsator observed by **CoRoT**

> **TESS** (WG8): Per sector, ≈100 sdB (plus a dozens of sdOs) among which ≈ 10 sdB pulsators (discovery and observations); g-, p-mode and hybrid pulsators

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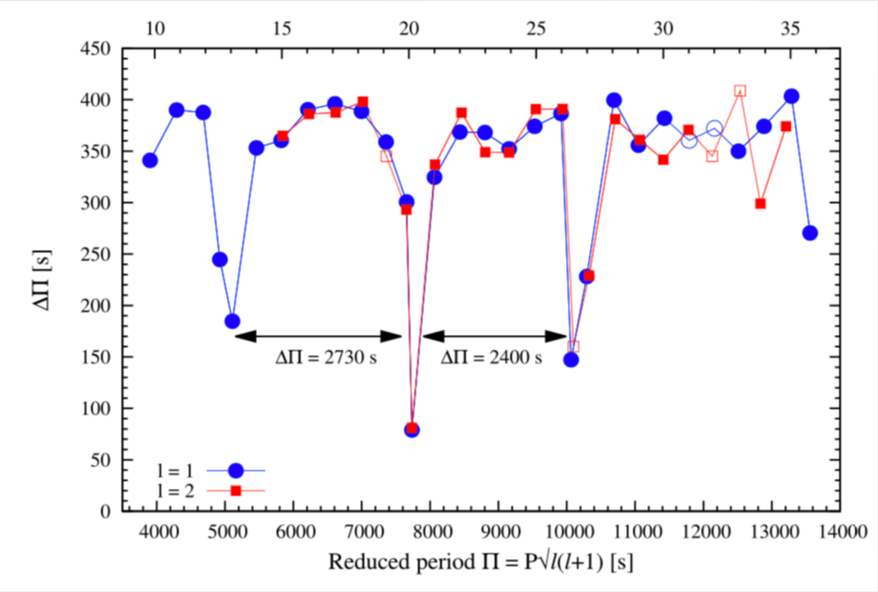
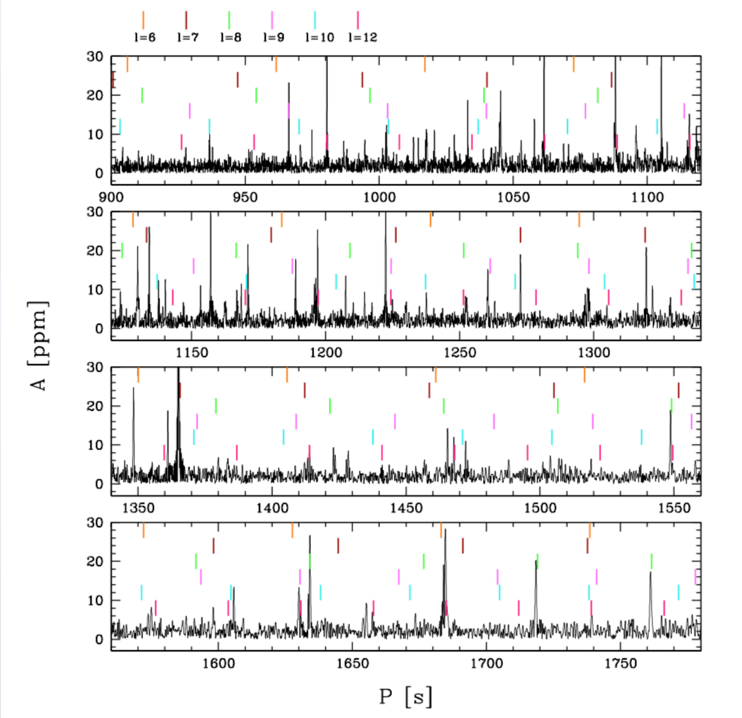
Marking results:

1. Observations of trapped g-modes (Østensen et al. 2014, Uzundag et al. 2017)
2. Observations of g-modes up to l=12 ! (Telting et al. 2014, Kern et al. 2018, Silvotti et al. 2019)



Østensen et al. 2014



Silvotti et al. 2019

Pulsations in compact stars: the space input

sdB stars:

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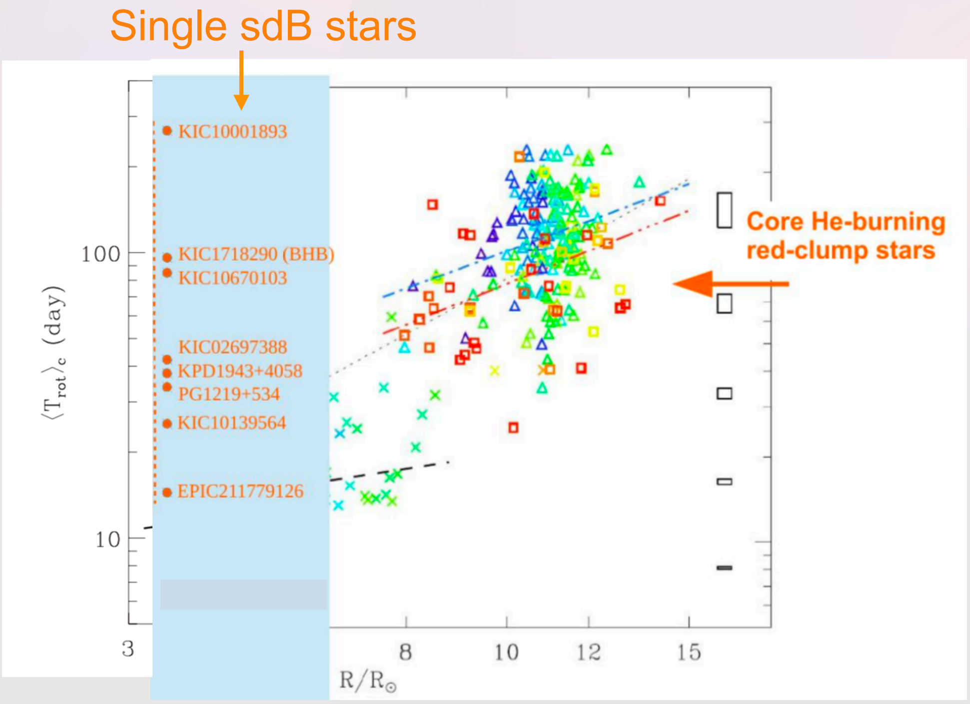
> **TESS** (WG8): ≈100 sdB (plus a dozens of sdOs) among which ≈ 10 sdB pulsators (discovery and observations) per sector; g-, p-mode and hybrid pulsators

Marking results:

3. single sdB stars are all slow rotators (Charpinet et al. 2018), in direct line with core rotation of Red Clump stars (Mosser et al. 2012) => indication of similar evolution (post-RGB stars)



Mosser et al. 2012
Charpinet et al. 2018

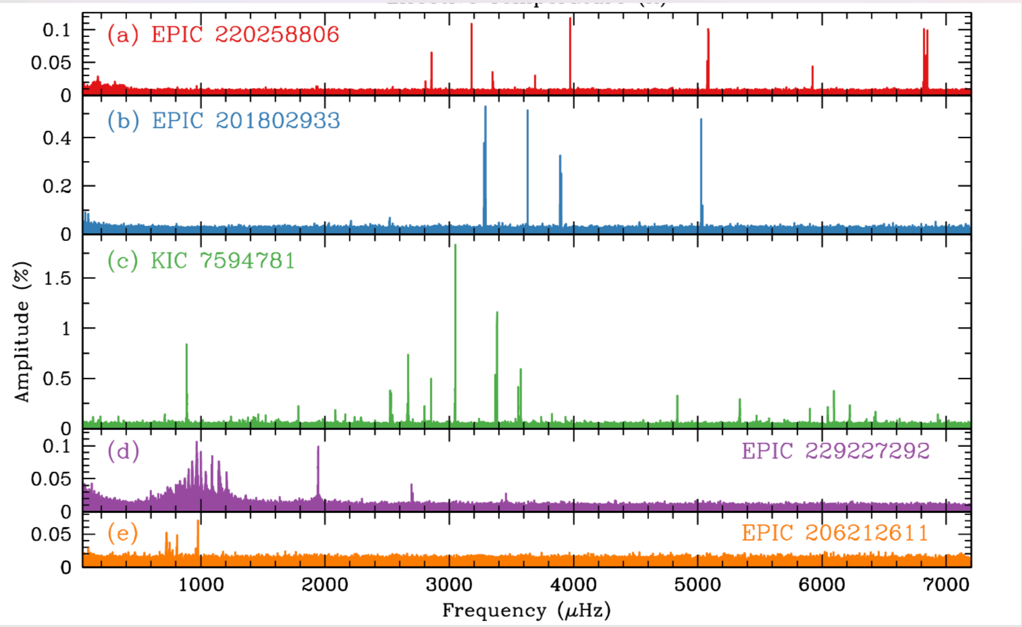
Pulsations in compact stars: the space input

White dwarfs:

> Kepler: 5 DAVs (only 2 for more than 1 quarter) and 1 DBV (23 months)
> K2: 22 DAVs, 1 DBV
> TESS (WG8): observations/discovery of several DAV, DBV & GW Vir pulsators (Bognar et al., Bell et al., Sowicka et al. in prep.)

Marking results:

4. Aperiodic, sporadic outbursting events in cool DAVs (but not the coolest): increase of stellar flux up to ~15% (Bell et al. 2017, Hermes et al. 2017)



Hermes et al. 2017

Pulsations in compact stars: the space input

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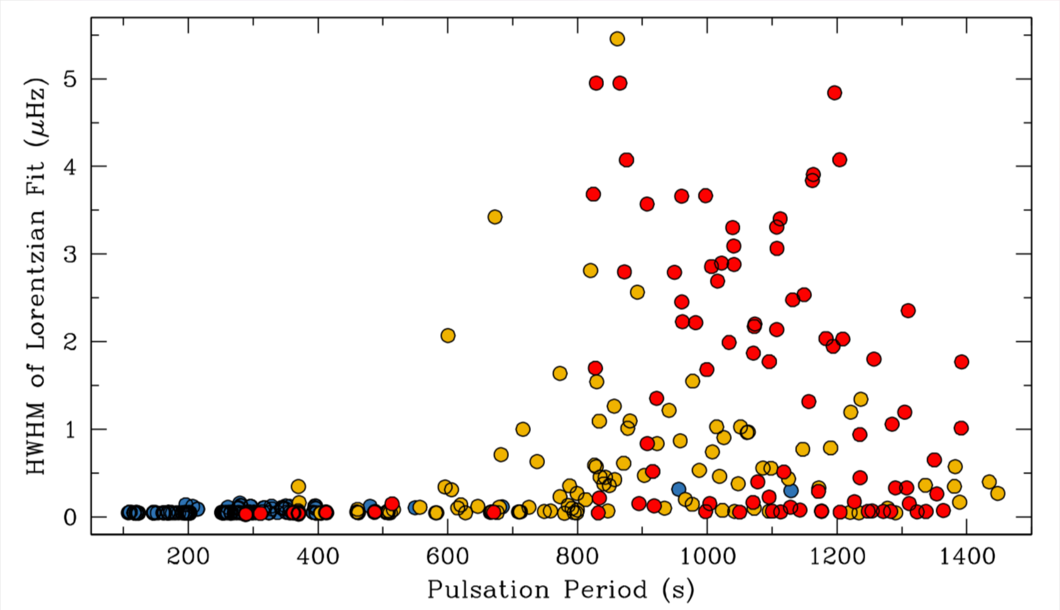
> K2: 22 DAVs, 1 DBV
> TESS (WG8): observations/discovery of several DAV, DBV & GW Vir pulsators (Bognar et al., Bell et al., Sowicka et al. in prep.)

Marking results:

5. In DAVs, dichotomy in mode line widths at weighted mean period of ~800 s (Hermes et al. 2017)



Hermes et al. 2017

Pulsations in compact stars: the space input

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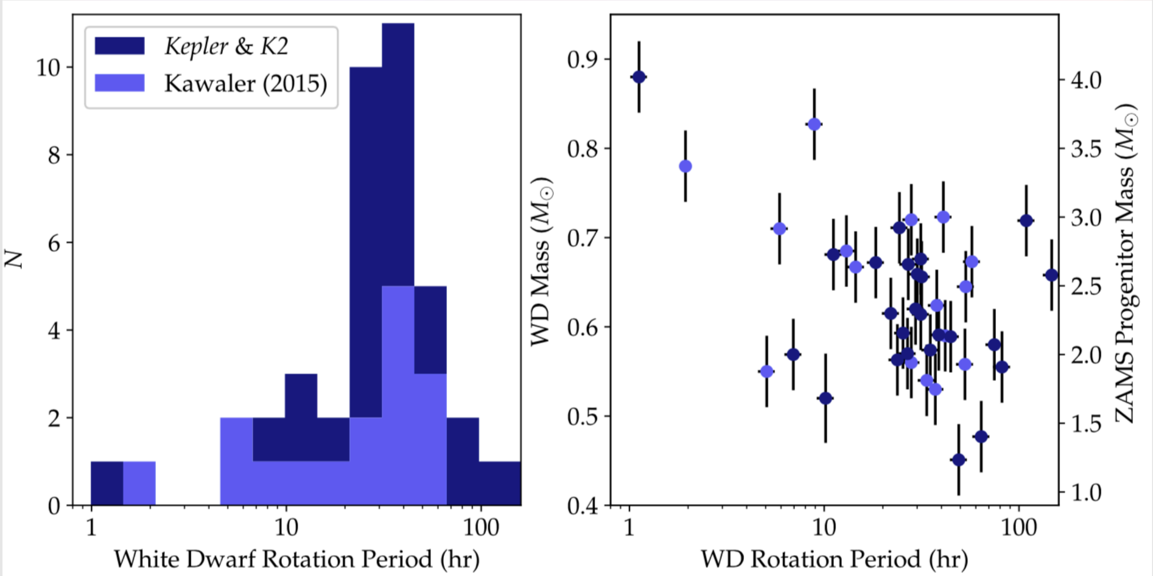
Marking results:

6. Rotation rates for white dwarfs, slow rotation + rotation rate as a function of mass (current & progenitor) (Hermes et al. 2017). No more Angular Momentum loss from HB phase (Charpinet et al. 2018)



Hermes et al. 2017

Pulsations in compact stars: the space input

White dwarfs:

> Kepler: 5 DAVs (only 2 for more than 1 quarter) and 1 DBV (23 months)
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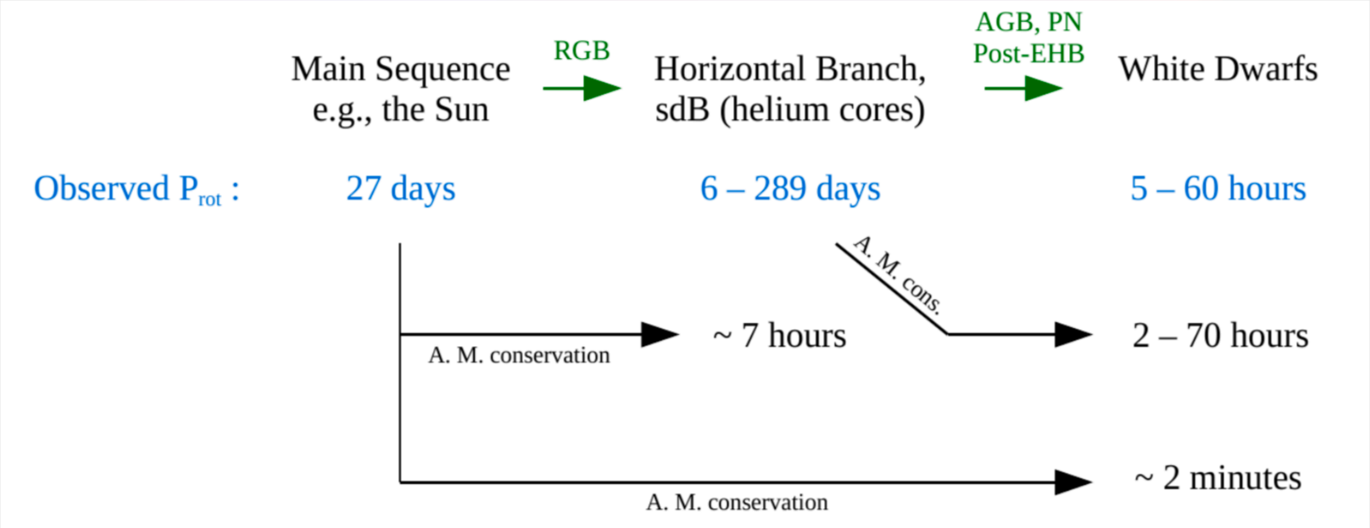

Charpinet et al. 2018

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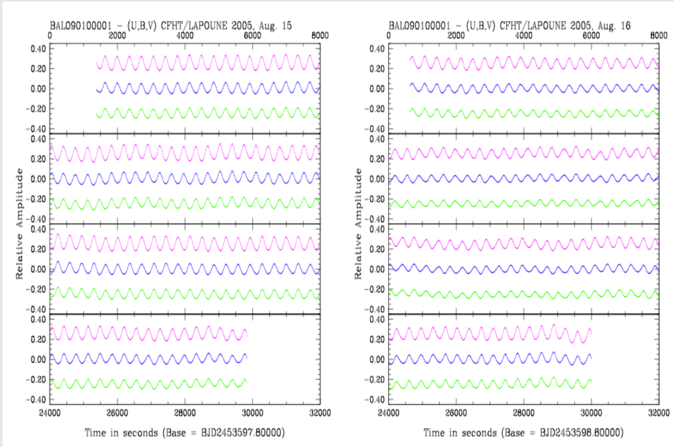
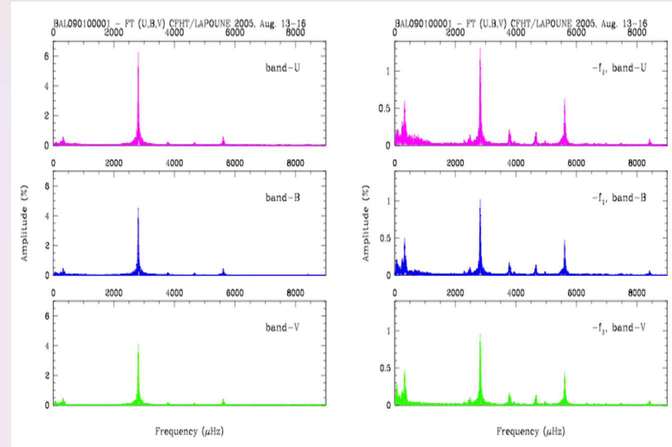
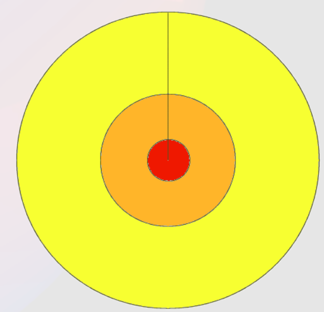
Method for forward asteroseismic modeling



Light curve



Frequencies extraction

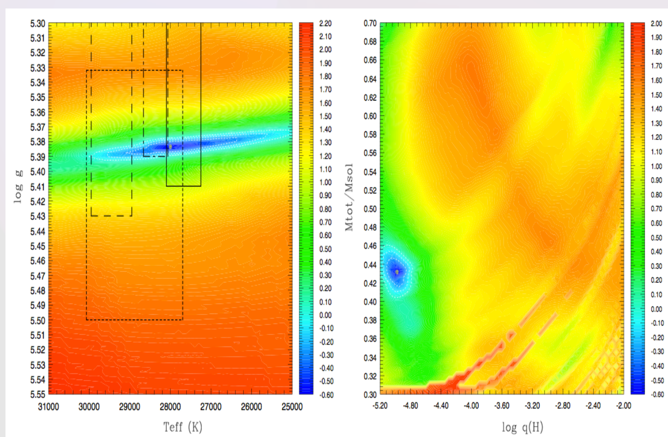


Static models

Minimisation of

$$S^2(a_1, a_2, ..., a_N) = \sum_{i=1}^{N_{\mathrm{obs}}} (P_{\mathrm{obs}}^{(i)} - P_{\mathrm{th}}^{(i)})^2$$

Genetic algorithms



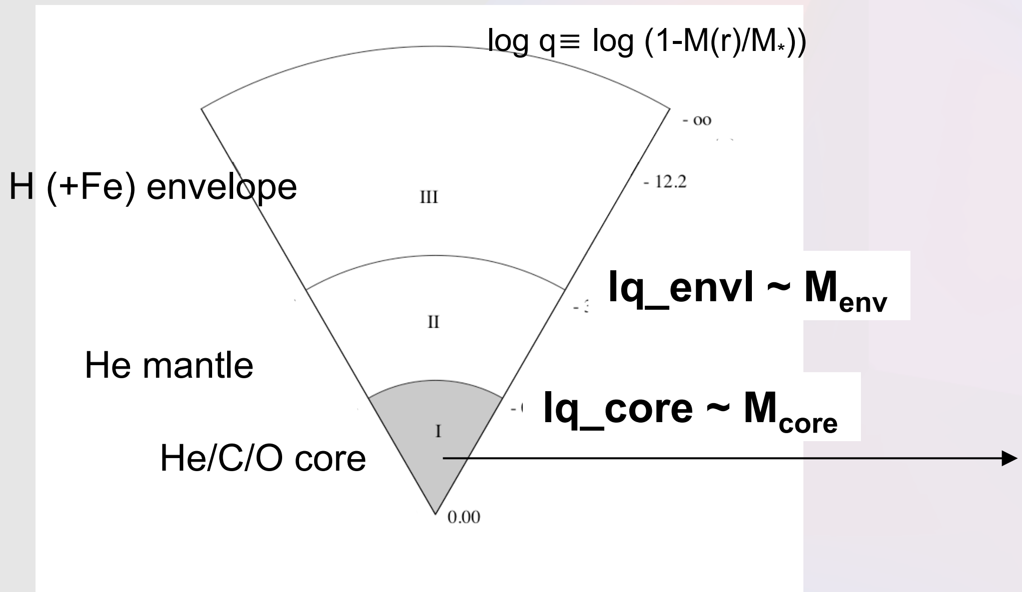
Optimal model = seismic solution

- log g
- T_{eff}
- M_*, R_*
- M_{env}
- M_{core}
- H, He, C, O profiles
- ...

Parameterized static models

Complete static equilibrium structures, *independent of stellar evolution*

sdB stars

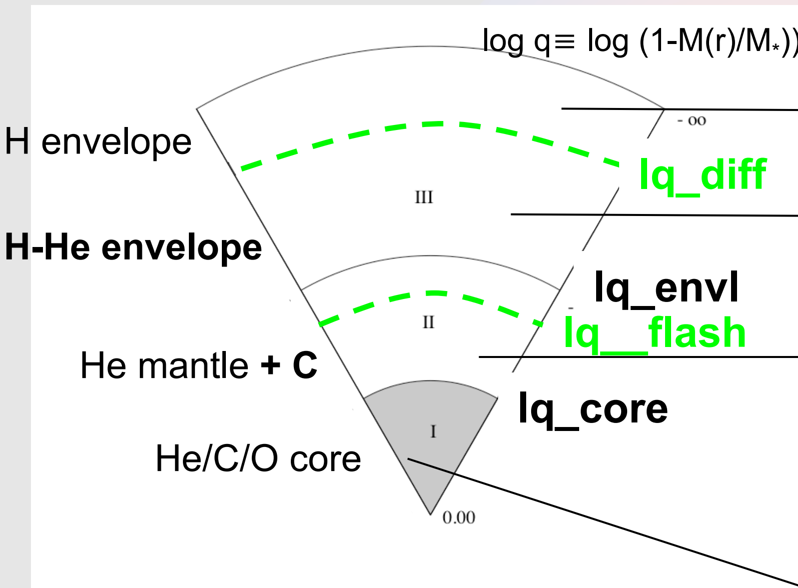


He_{core}, O_{core} (with He+C+O=1)

Parameterized static models

Complete static equilibrium structures, *independent of stellar evolution*

sdB stars



Envelope with double transition:

Pure H envelope

H/He envelope (+Fe)
(**Henv,diff**)

0 - 8 % of C (**C_flash**)
in the He mantle on 0 - 100%
(**lq_flash**) of the mantle
produced by He-flash

He_{core}, O_{core}

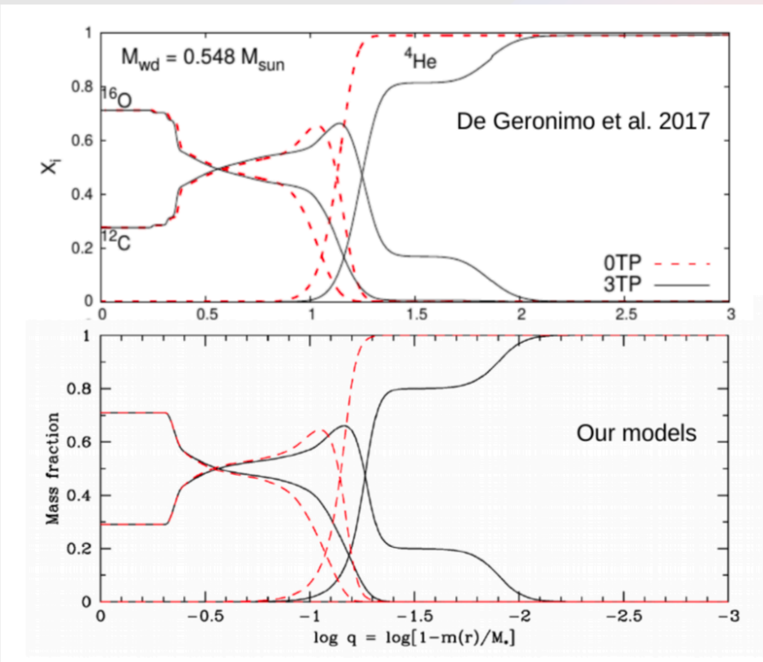
+ chemical transition profiles (smooth to steep): **pf_diff**, **pf_env**, **pf_flash** & **pf_core**
+ total mass of the star **M_***

= 4th generation (4G) models of sdB stars, up to 13 parameters

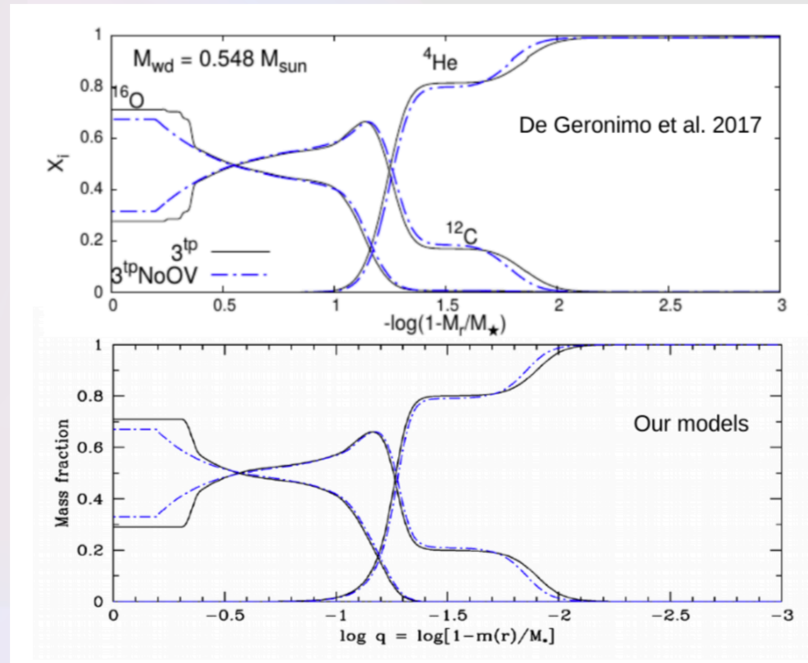
Parameterized static models

Complete static equilibrium structures, *independent of stellar evolution*

White dwarfs



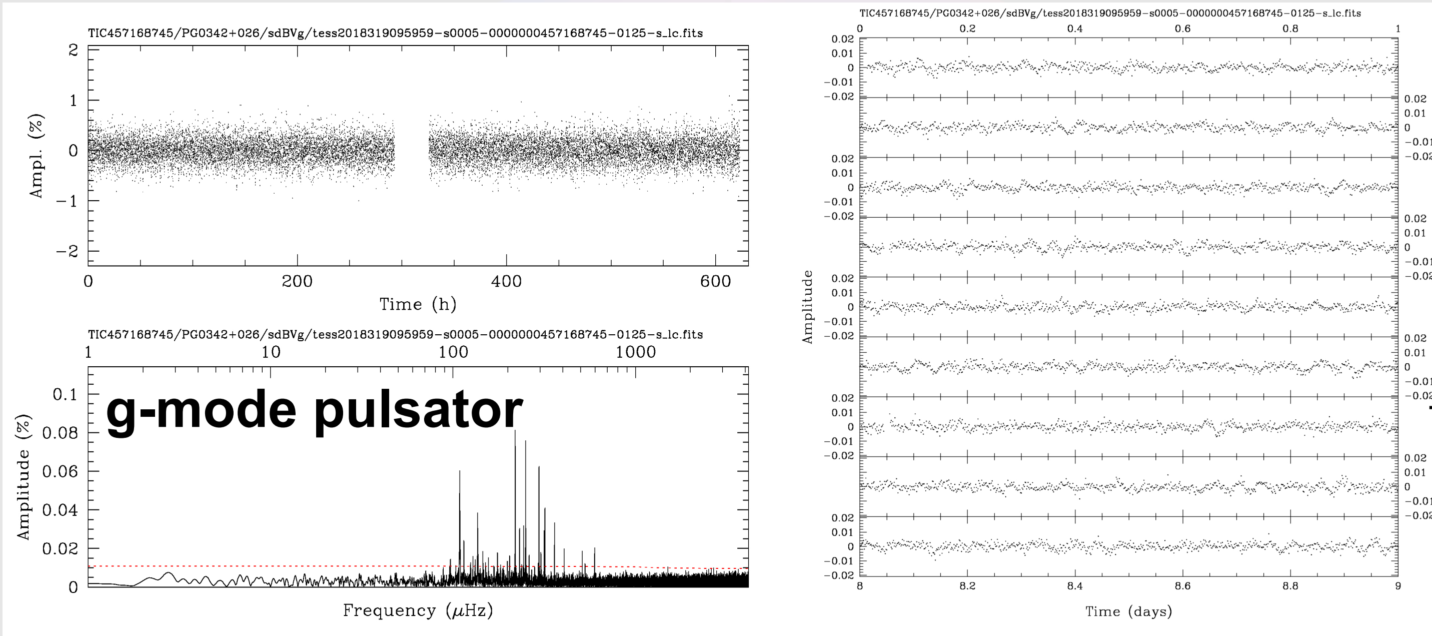
Charpinet et al. 2019, EuroWD21, in press



Charpinet et al. 2019, EuroWD21, in press

Typical configurations predicted by standard evolution models can be reproduced by our static ones and can be found in our optimization computations... if optimal

Modeling TESS target PG 0342+026 (Sector 5)



TIC457168745

- Frequency analysis with FELIX (Charpinet et al. 2010), above 4.6σ: **27 independent g-modes** (1674 s − 10331 s)
- Atmospheric parameters (D. Schneider 2019):

$$T_{eff} = 25{,}700 \pm 300 \text{ K}$$
$$\log g = 5.48 \pm 0.03$$

Modeling TESS target PG 0342+026 (Sector 5)

Search the stellar model(s) whose theoretical periods best fit the observed ones, in order to minimize

$$S^2(a_1, a_2, ..., a_N) = \sum_{i=1}^{N_{\rm obs}} (P_{\rm obs}^{(i)} - P_{\rm th}^{(i)})^2$$

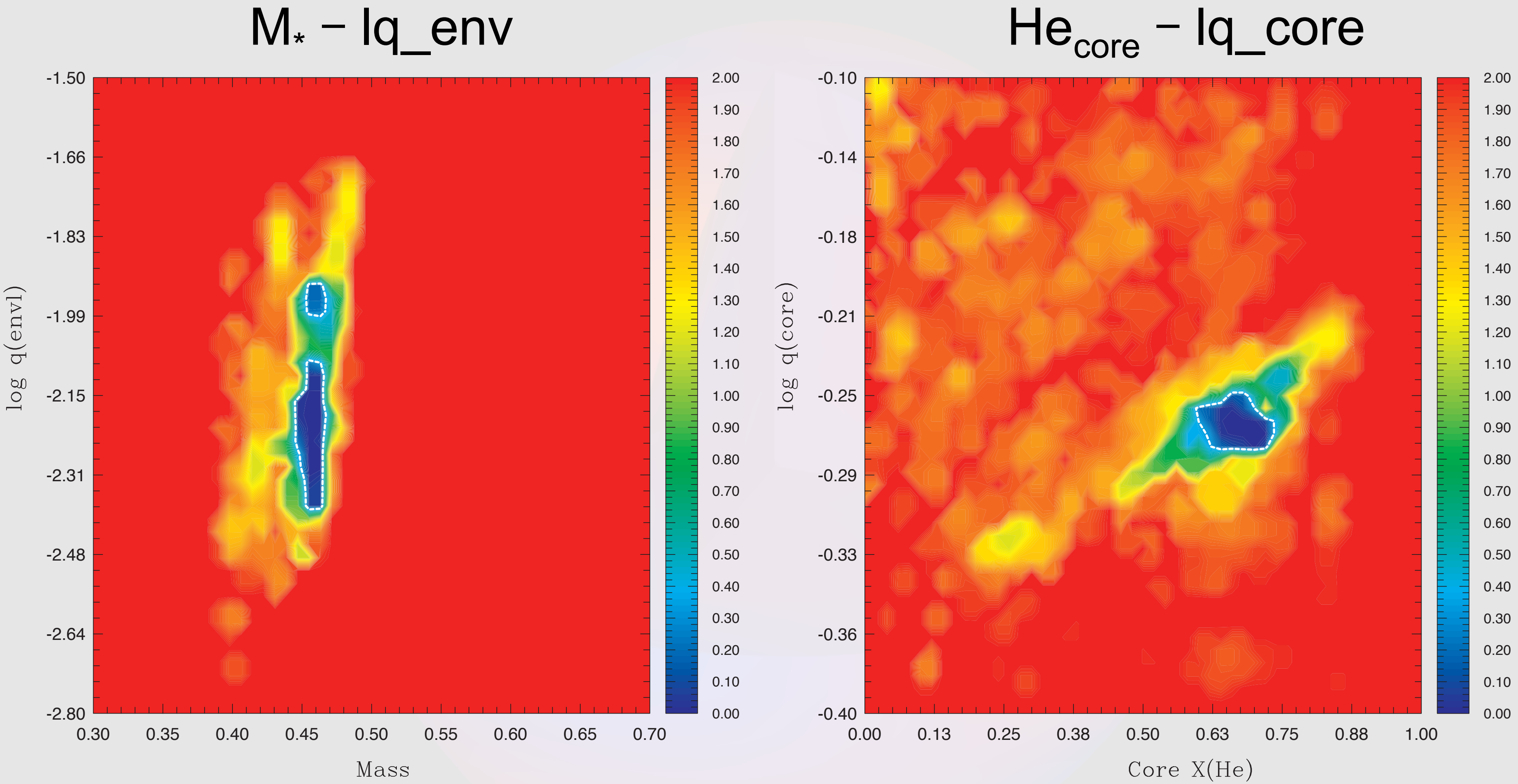
> **Optimization procedure**: Efficient optimization codes (based on *Genetic Algorithms*) to thoroughly explore the parameter space and find the minima of S^2

Under *external* constraints from spectroscopy in the 13-parameters space:

- $0.3 \leq$ **M***≤ 0.7 M_{sun} (Han et al. 2002, 2003)
- $-3.0 \leq$ **lq_env** ≤ -1.5
- $-0.40 \leq$ **lq_core** ≤ -0.10
- $0 \leq$ **He_{core}** ≤ 1
- $0 \leq$ **O_{core}** ≤ 1
- **$H_{env,diff}$**: 60-100% + location of the transition **lq_diff**
- **C_{flash}**: 0-8% + location of the transition **lq_flash**
- Steep to smooth profiles (pro_fac parameters: **pf_diff**, **pf_env**, **pf_flash** and **pf_core**)

\+ T_{eff}, log g @ 3σ spectroscopy

Modeling TESS target PG 0342+026

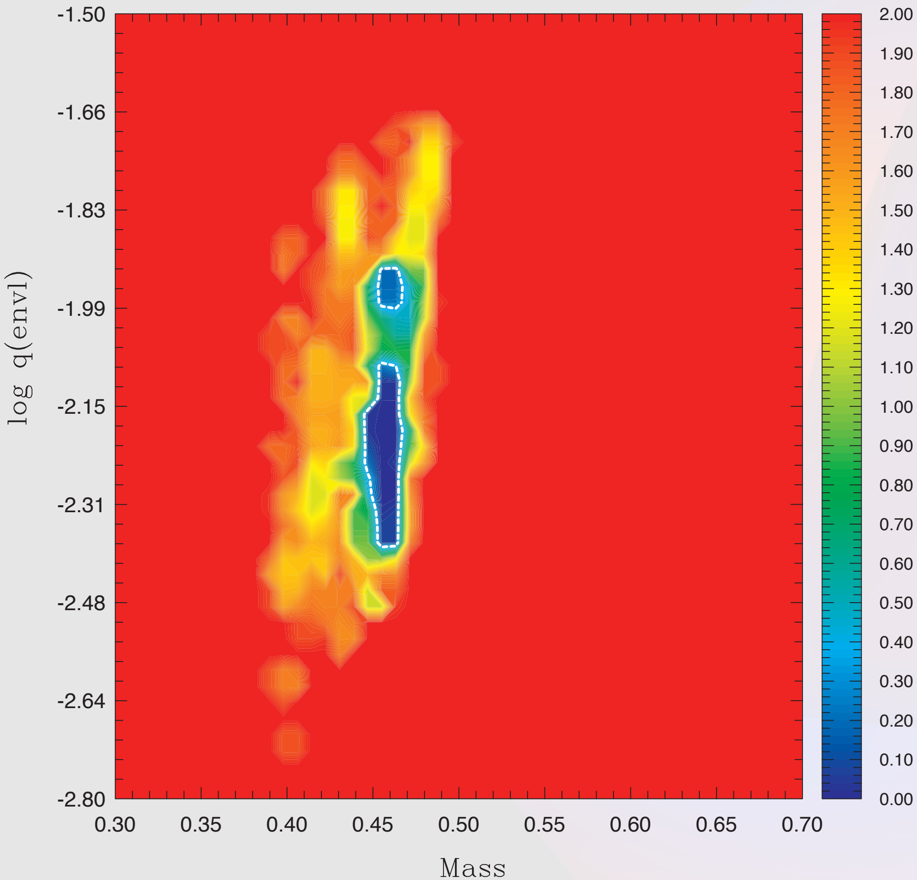


One clear solution emerged:

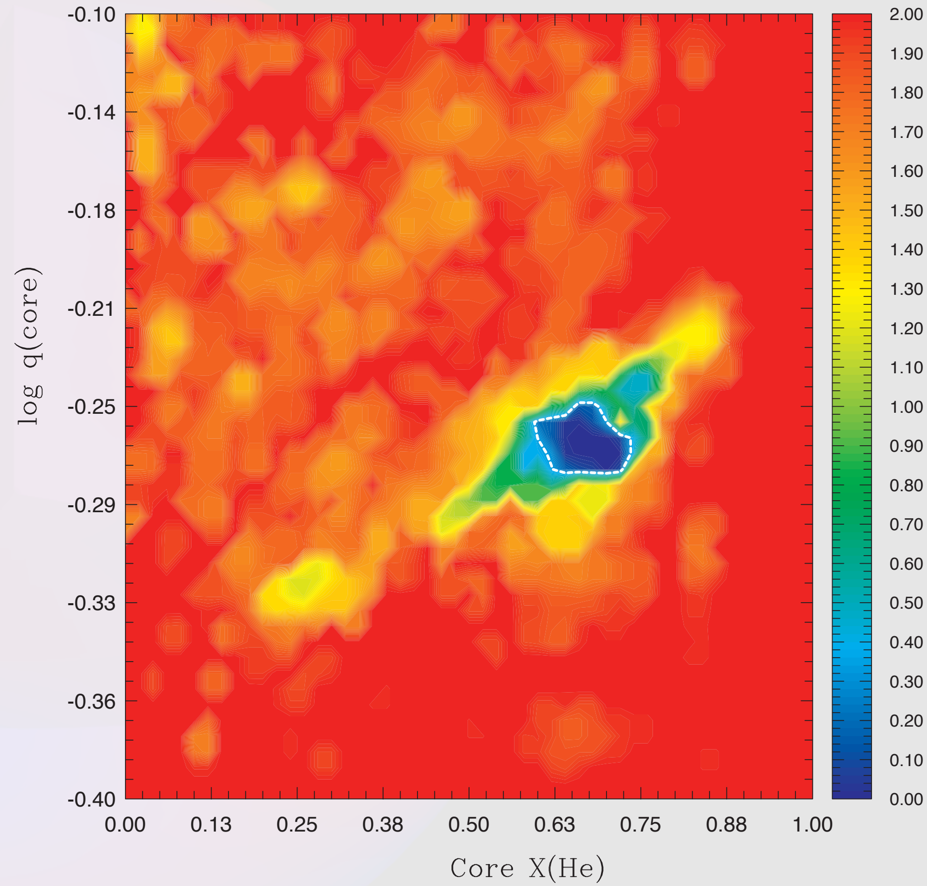
$S^2=0.20$, $\overline{dP/P}\sim0.07\%$, $\overline{dP}=3.5s$, $\overline{d\nu}=0.17\ \mu Hz$

Modeling TESS target PG 0342+026

$M_* - lq\_env$



$He_{core} - lq\_core$



$M_* = 0.452^{+0.007}_{-0.005} M_{sun}$

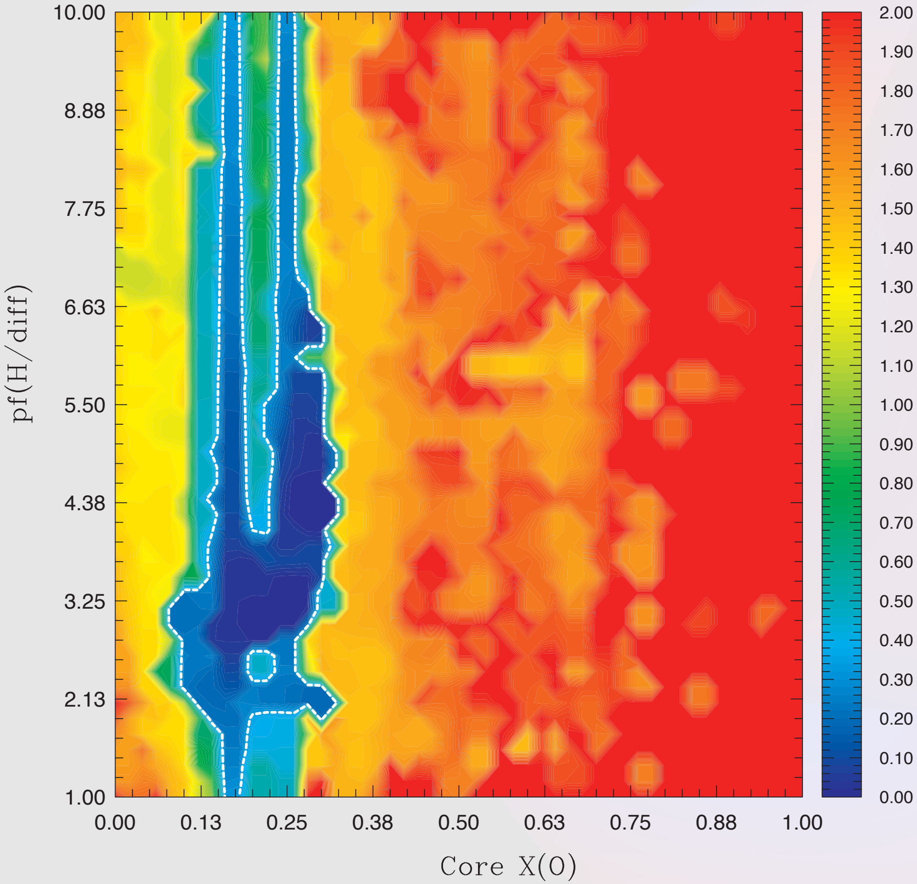
$lq\_env = -2.28^{+0.27}_{-0.07}$

$He_{core} = 0.68^{+0.05}_{-0.09}$

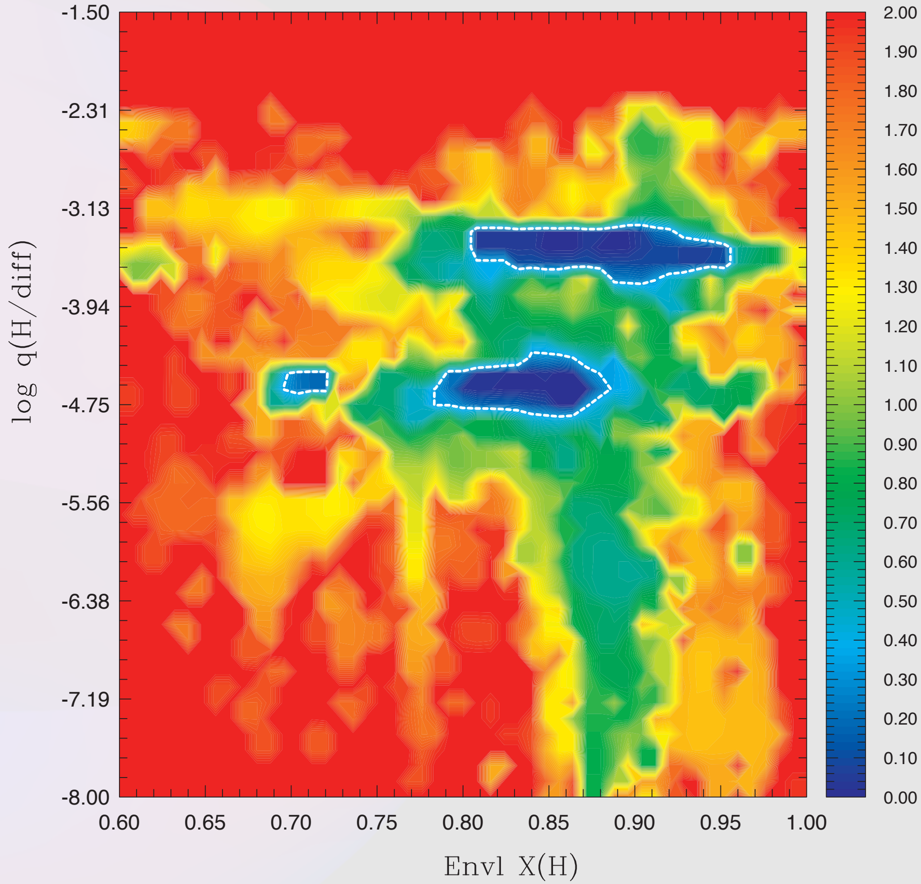
$lq\_core = -0.27^{+0.02}_{-0.01}$

Modeling TESS target PG 0342+026

O_{core} – Pf_diff



$H_{env,diff}$ – lq_diff



$O_{core} = 0.27^{+0.02}_{-0.16}$

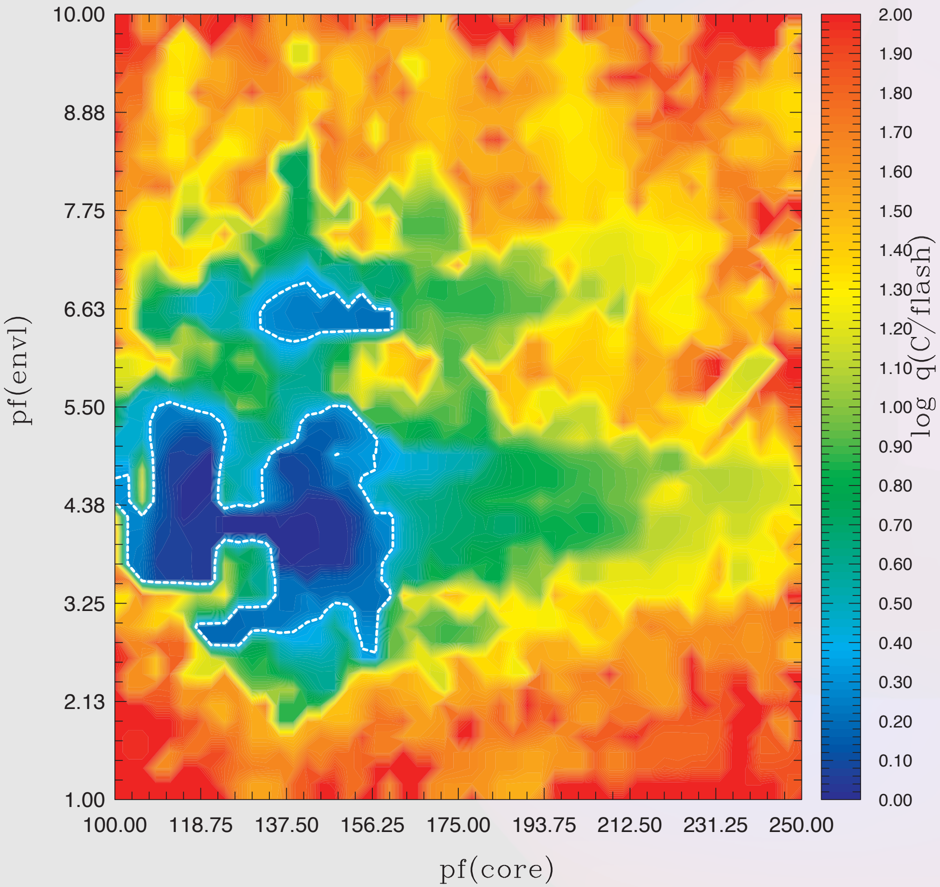
Pf_diff unconstrained

$H_{env,diff} = 0.86^{+0.07}_{-0.09}$

$lq\_diff = -3.41^{+0.03}_{-2.57}$

Modeling TESS targets: TIC 169285097

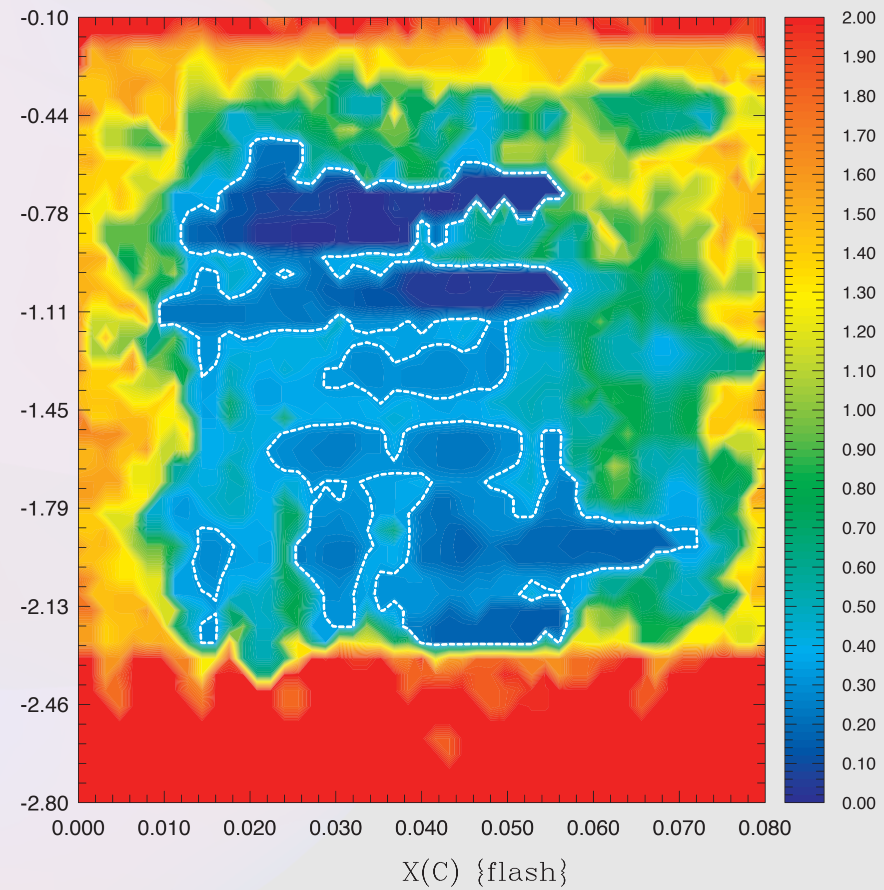
Pf_core – Pf_env



Pf_core=121$^{+40}_{-10}$

Pf_env=4.9$^{+1.6}_{-1.8}$

C_{flash} – lq_flash



C_flash = 4±2%

lq_flash = -0.75 $^{+0.03}_{-1.26}$

+ Pf_flash unconstrained

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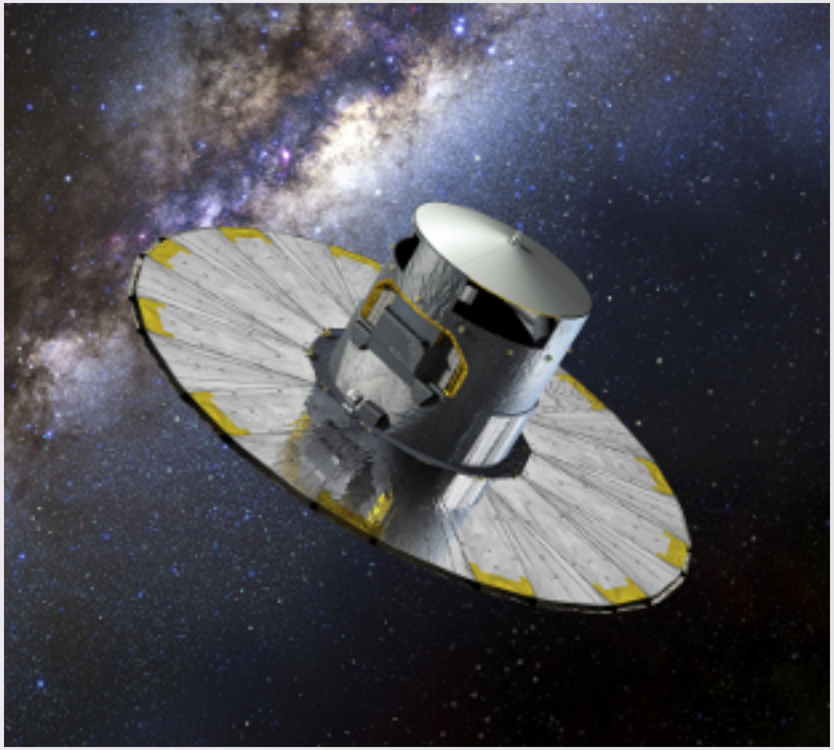
Testing the seismic results

New possibilities with GAIA

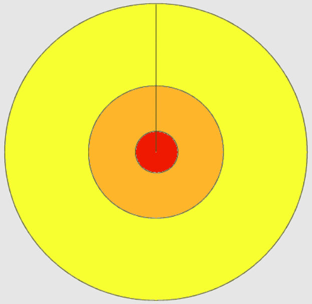
- GAIA provides high quality parallaxes/ distance estimates =>

1. Possibility to cross-check with **distance** derived based on seismic stellar parameters
2. Combined to spectroscopy, possibility to to cross-check with **mass** derived from asteroseismology

To date: asteroseismic solutions available for a sample of **18** sdB pulsators



Test 1: Method for deriving asteroseismic distances

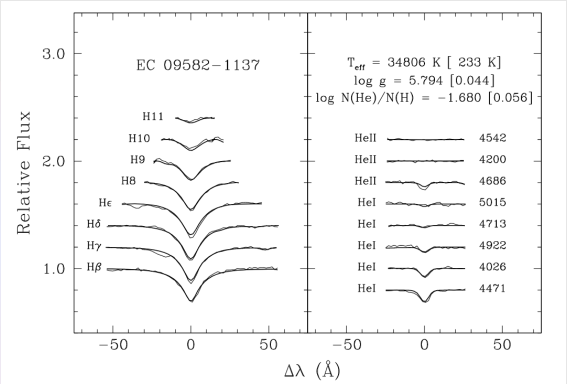


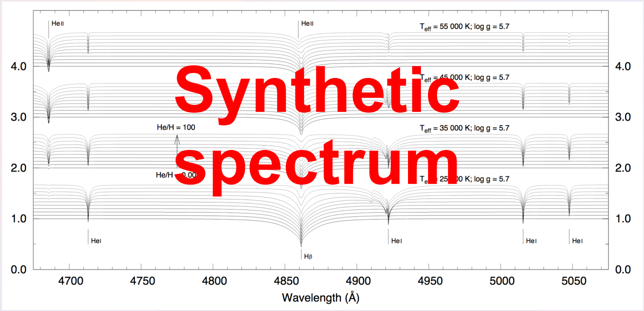
Asteroseismology

- log g
- T_{eff}
- M_*

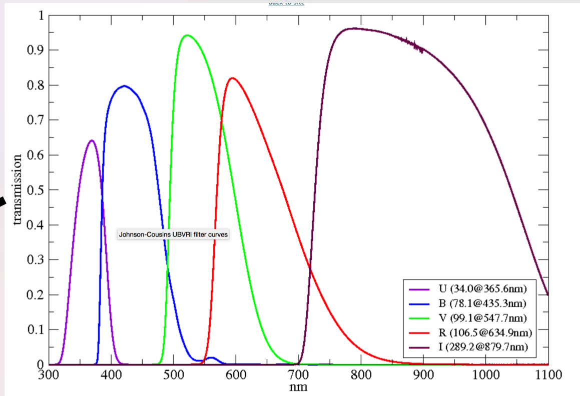
N(He)/N(H)

Spectroscopic fitting





Synthetic spectrum



Absolute magnitude M_a

Bandpass of filter a

Absorption coefficient:
Bandpass+E(B-V)

Apparent magnitude a

Asteroseismic distance

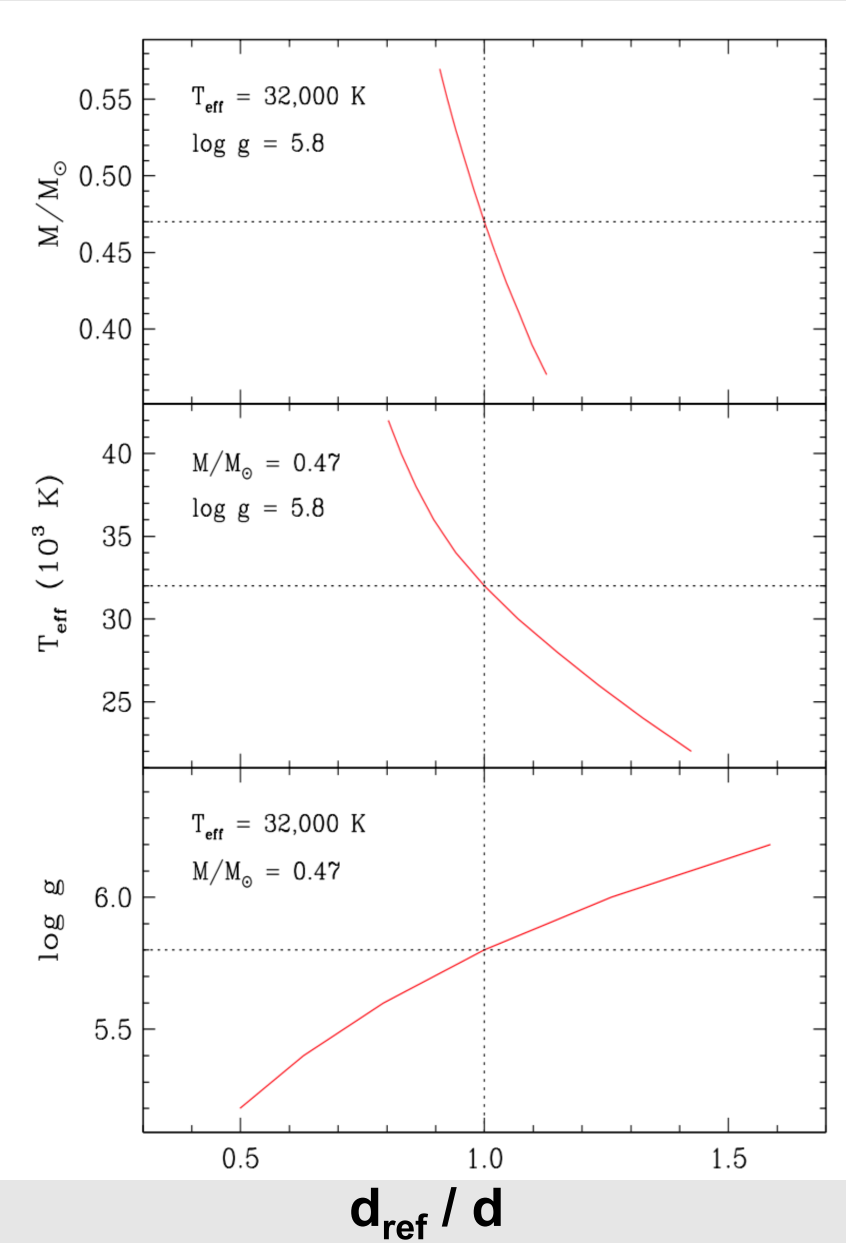
Test 1: The sdB asteroseismic sample

18 sdB stars modeled by asteroseismology

Name	log g (cm s^{-2})	$T_{\rm eff}$ (K)	M ($M_\odot$)	References
PG 1047+003	5.800±0.006	33000±1600	0.490±0.014	Charpinet et al. (2003)
PG 0014+067	5.775±0.009	33940±3520	0.477±0.024	Charpinet et al. (2005a)
PG 1219+534	5.807±0.006	33640±1360	0.457±0.012	Charpinet et al. (2005b)
Feige 48	5.437±0.006	29580±370	0.460±0.008	Charpinet et al. (2005c)
EC 05217−3914	5.730±0.008	32000±1800	0.490±0.020	Billères & Fontaine (2005)
PG 1325+101	5.811±0.004	35050±220	0.499±0.011	Charpinet et al. (2006a)
PG 0048+091	5.711±0.010	33300±1700	0.447±0.027	Charpinet et al. (2006b)
EC 20117−4014	5.856±0.008	34800±2000	0.540±0.040	Randall et al. (2006a)
PG 0911+456	5.777±0.002	31940±220	0.390±0.010	Randall et al. (2007)
BAL 090100001	5.383±0.004	28000±1200	0.432±0.015	Van Grootel et al. (2008)
EC 09582−1137	5.788±0.004	34805±230	0.485±0.011	Randall et al. (2009)
KPD 1943+4058	5.520±0.030	28050±470	0.496±0.002	Van Grootel et al. (2010a)
KPD 0629−0016	5.450±0.034	26290±530	0.471±0.002	Van Grootel et al. (2010b)
KIC 02697388[a]	5.489±0.033	25622±420	0.463±0.009	Charpinet et al. (2011)
KIC 02697388[b]	5.499±0.049	25555±520	0.452±0.011	Charpinet et al. (2011)
PG 1336−018	5.739±0.002	32780±200	0.459±0.005	Van Grootel et al. (2013)
TIC 278659026	5.572±0.056	23738±640	0.391±0.013	Charpinet et al. (2019)

+ PB8783 (Van Grootel et al. 2019) + PG 0342+026 (this work)

Test 1: distance dependence on M_*, T_{eff} and log g

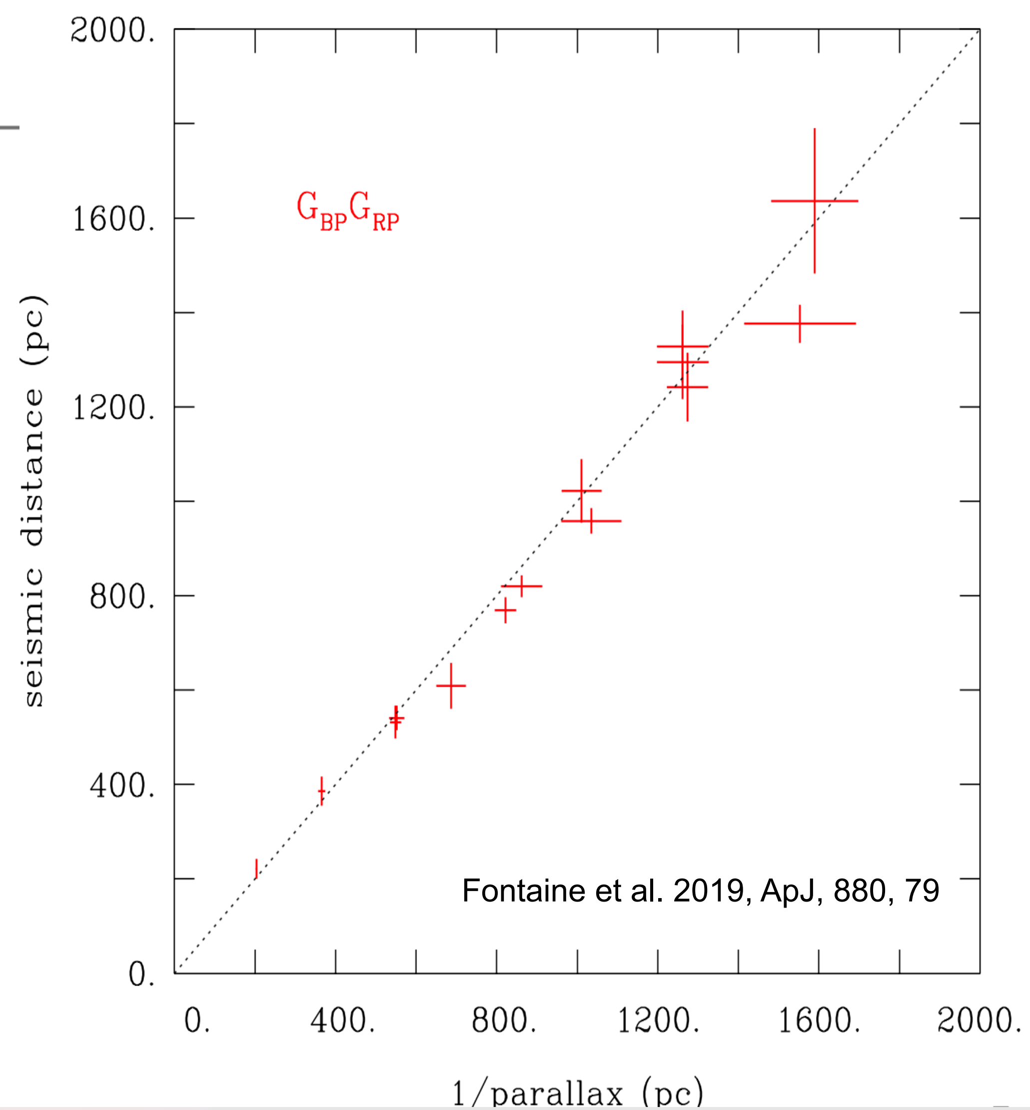


- Representative sdB model: T_{eff} = 32,000 K, log g = 5.8, M = 0.47 $M_\odot$ -> reference distance $\mathbf{d_{ref}}$
- Distance **d** computed by varying one of the seismic parameters and keeping the other two constant
- Considering "expected" parameter ranges for sdBs, **changing the mass can account for a ± 10% variation in derived asteroseismic distance**
- log g and T_{eff} have a larger effect on the distance if considering the full ranges where sdBs are found (but small effect over typical measurement uncertainties)

Fontaine et al. 2019, ApJ, 880, 79

Results of Test 1: seismic vs GAIA distances

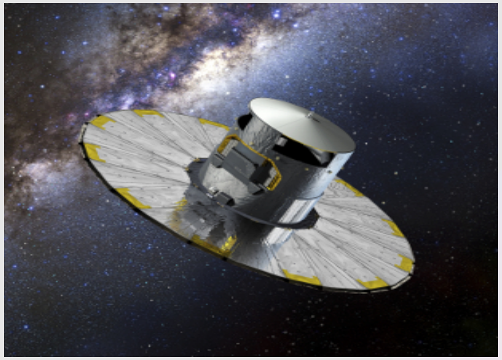
Name	d(Gaia) (pc)	$d(G_{BP}G_{RP})$ (pc)
PG 1047+003	687±37	609±49
PG 0014+067	2794±1037	1812±277
PG 1219+534	549±14	532±35
Feige 48	822±27	769±28
EC 05217−3914	1590±108	1636±154
PG 1325+102	862±51	820±23
PG 0048+091	1058±48	...
EC 20117−4014	587±13	...
PG 0911+456	1035±75	958±27
BAL 090100001	365.6±8.6	386±31
EC 09582−1137	1553±139	1376±40
KPD 1943+4058	1274±51	1242±73
KPD 0629−0016	1011±50	1022±67
KIC 02697388[b]	1262±64	1328±76
KIC 02697388[c]	1262±64	1295±79
PG 1336−018	552±19	541±26
TIC 278659026	203.7±2.1	221±21



All distances agree within 1sigma

Test 2: Method for deriving “spectroscopic” masses

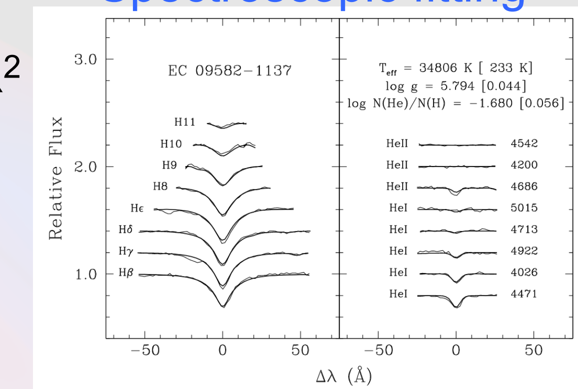
GAIA



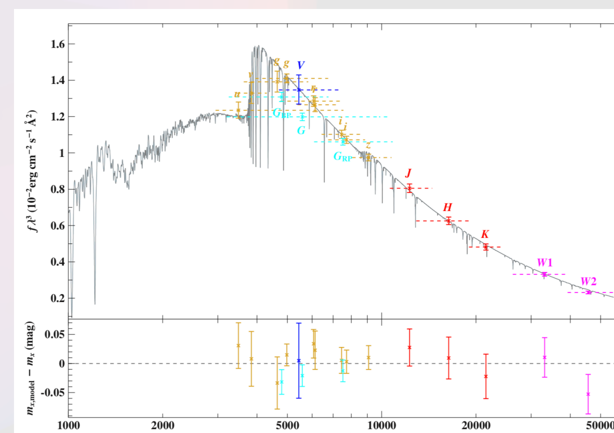
- distance d/parallax ϖ

- $\log g = GM/R^2$
- T_{eff}

Spectroscopic fitting



Spectral energy distribution (SED) fitting to colors (photometry)

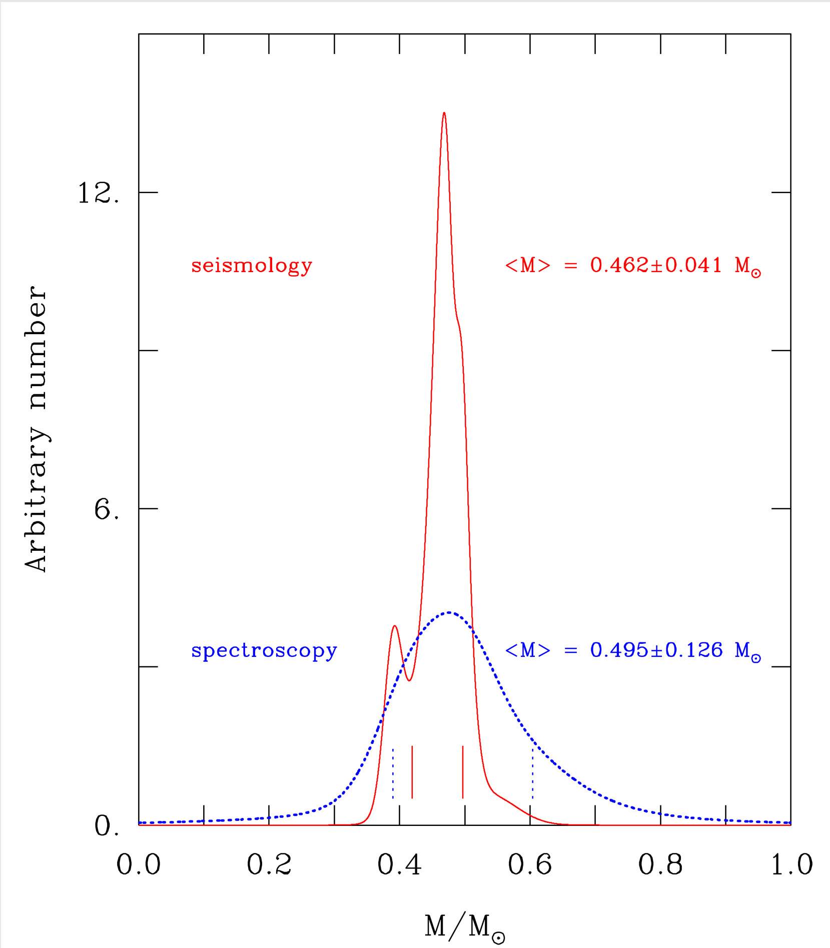


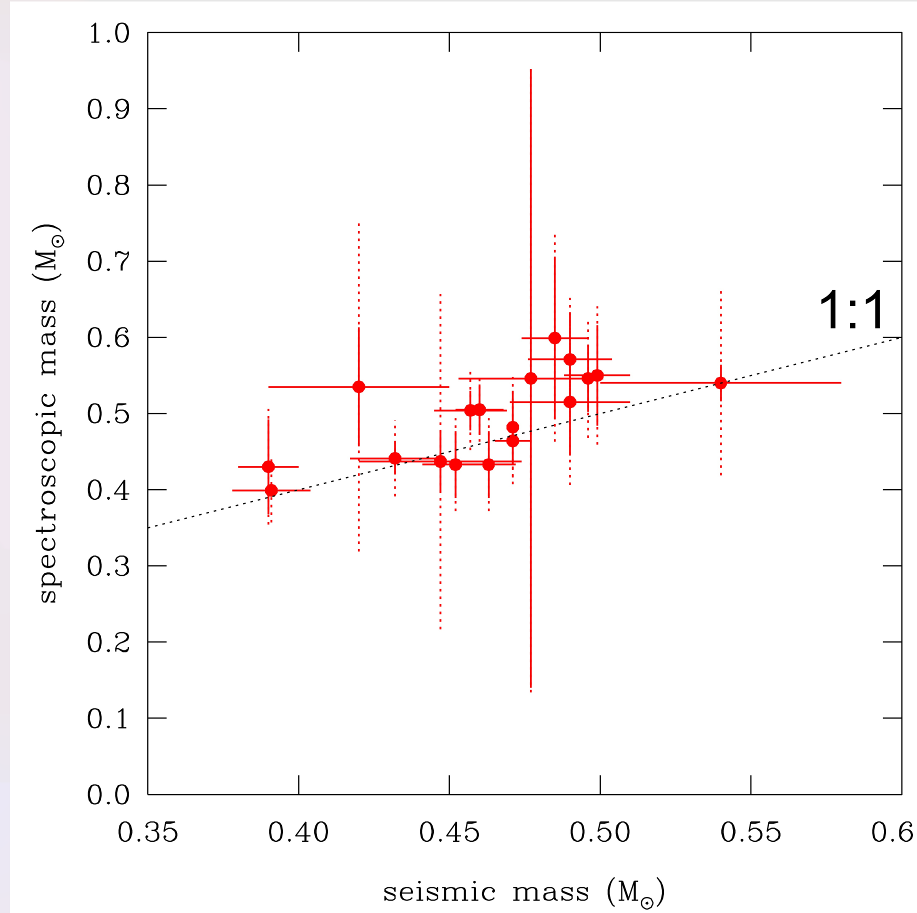
- Angular diameter
$\theta \approx 2R/d$ (if $\theta \ll 1$)

« Spectroscopic » mass

$$M = g\theta^2 / 4G\varpi^2$$

Results of test 2: seismic vs spectroscopic masses





Fontaine et al., in prep.

$\Delta M/M$ seismology ~ 10%

$\Delta M/M$ spectroscopy ~ 25%

Outline

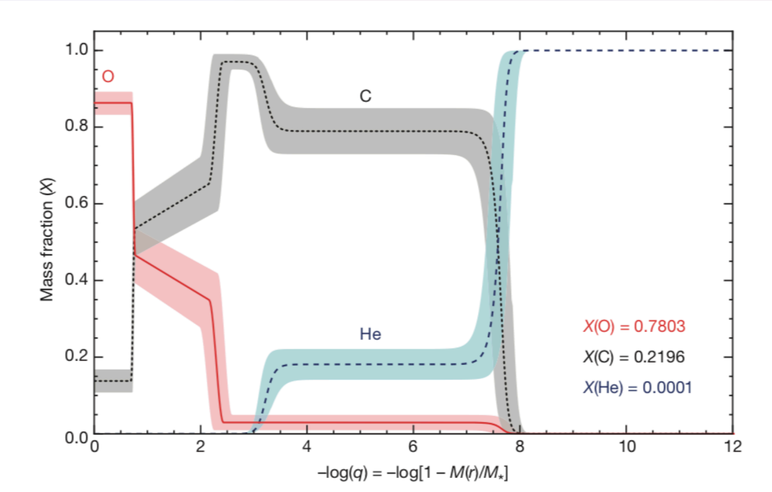
The current benchmark: KIC 08626021

- DBV pulsator, observed during 23 months in the original *Kepler* mission
- 8 well-secured independent modes in the range 143.2 − 376.1 s
- Close to hot edge: T_{eff} = 29,360 ± 780 K, log g=7.89 ± 0.05

Seismic optimization with static parametrized models, based on L(r) α M(r) profiles (Giammichele et al. 2018, Nature, 554, 73):

✓ **Reproduction of the 8 periods at the precision of the observations** (Δν ~ 0.6 nHz or ΔP ~ 38 μs)

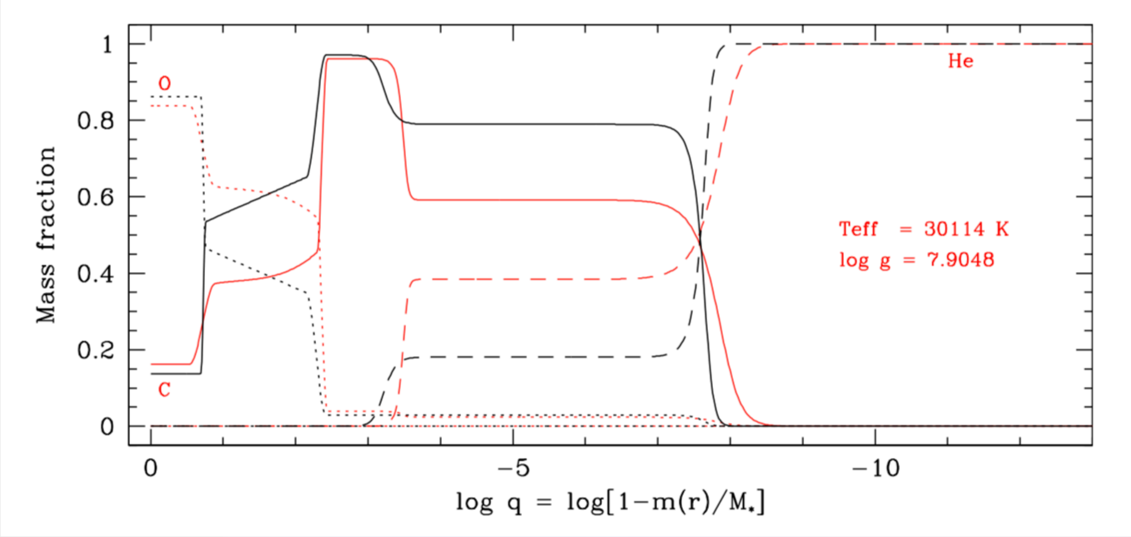
✓ **Core ~15% richer in O (in mass) and ~40% more massive than expected from standard evolutionary models**



Giammichele et al. 2018

The current benchmark: KIC 08626021

- **A legitimate problem**: in hot DBVs, still active neutrino cooling makes L(r) $\not\propto$ M(r) (Timmes et al. 2018) -> shift in frequencies about 30μHz (up to 70 μHz)
- Charpinet et al. 2019 (A&A, 628, L2): corrected L(r) profiles => new asteroseismic solution and chemical profiles



Giammichele et al. 2018

Charpinet et al. 2019

Global parameters and main conclusions on core size and composition are unchanged

Preliminary results for five DAV pulsators

	KIC11911480	L19-2	SDSSJ1136+0409	EPIC220258806	EPIC220347759
$T_{\rm eff}$ (spectro)	12,026 $\pm$ 195	12,058 $\pm$ 184	12,330 $\pm$ 260	12,807 $\pm$ 219	12,692 $\pm$ 214
$T_{\rm eff}$ (astero)	12,300 $\pm$ 485	12,021 $\pm$ 717	12,297 $\pm$ 195	12,163 $\pm$ 417	12,478 $\pm$ 329
$\log g$ (spectro)	8.00 $\pm$ 0.05	8.11 $\pm$ 0.05	7.99 $\pm$ 0.06	8.1 $\pm$ 0.05	8.09 $\pm$ 0.05
$\log g$ (astero)	8.01 $\pm$ 0.04	8.13 $\pm$ 0.06	8.06 $\pm$ 0.04	8.07 $\pm$ 0.02	8.11 $\pm$ 0.05
d (astero)	184.2 $\pm$ 14.6	21.0 $\pm$ 0.5	127.7 $\pm$ 7.2	79.6 $\pm$ 3.0	141.7 $\pm$ 7.0
d (parallax)	182.9 $\pm$ 4.1	20.93 $\pm$ 0.01	130.7 $\pm$ 1.9	80.56 $\pm$ 0.54	151.8 $\pm$ 3.5
Other relevant parameters derived from asteroseismology (see text for details)					
Mass ($M_\odot$)	0.63	0.68	0.63	0.64	0.67
$\log q$(H)	-3.12	-4.39	-5.55	-4.23	-4.42
$\log q$(He)	-1.42	-1.87	-1.75	-1.91	-2.40
$\log q$(core)	-0.66	-0.80	-0.77	-0.37	-0.74
O(core)	0.85	0.82	0.75	0.88	0.85

Charpinet et al. 2019, EuroWD21, in press

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Similar pattern for 4 DAVs: core ~15% richer in O and ~40% more massive than expected from standard evolutionary models

This provides strong constraints on processes shaping stellar cores during the preceding He-burning phase

He-burning cores in sdB stars

Star	M* (M_{sun})	Mcore (M_{sun})	Hecore	Ocore
KPD0629-0016 (Van Grootel et al. 2010)	0.471 ± 0.002	0.22 ± 0.01 (47% M_*)	0.59 ± 0.01	-
KIC02697388 (Charpinet et al. 2011)	$0.452^{+0.018}_{-0.005}$	$0.225^{+0.011}_{-0.016}$ (49% M_*)	$0.73^{+0.07}_{-0.12}$	-
TIC278659026 (Charpinet et al. 2019)	0.391 ± 0.009	0.198 ± 0.001 (50% M_*)	$0.58^{+0.06}_{-0.03}$	$0.16^{+0.13}_{-0.05}$
PG 0342+026 (This work)	$0.452^{+0.007}_{-0.005}$	$0.209^{+0.011}_{-0.016}$ (46% M_*)	$0.68^{+0.05}_{-0.09}$	$0.27^{+0.02}_{-0.16}$

Very similar cores, all significantly bigger (and more O-rich ?) than expected from stellar evolution

Outline

I. Pulsations in hot subdwarf and white dwarf stars
   a. Introduction
   b. Some marking results from space observations
II. Models and method for asteroseismic modeling
III. Testing the sdB seismic results with GAIA
IV. Seismic modeling of white dwarfs
V. **Conclusions**

Conclusions

- ✓ Space observations are crucial for g-modes of compact pulsators
- ✓ Some marking results from Kepler:
  - Observations of g-modes in sdB stars up to l=12 !
  - Consistent picture of Angular Momentum along evolution: loss during/before RGB phase, no more after

- ✓ Forward modeling approach with static parametrized models is successful for sdB/WD asteroseismology:
  - ✓ Global parameters and internal structures determined with a very high precision
  - ✓ sdB distances and masses fully consistent with GAIA results
  - ✓ **He-burning cores are bigger (and more enriched in O) than predicted from stellar evolution**